

MATLAB and K-Wave Based Outdoor Ray Propagation Predictor Tool SNELLIX for Surface Wave Modelling

Neha, Dr.Baljeet kaur
Department of Electronics and Communication Engineering, Guru Nanak Dev Engineering College
Ludhiana, Punjab, India

Abstract
This paper discusses the overview of ground wave propagation and addresses a particular class of propagation scenarios in the presence of surface terrain and atmospheric refractivity. Traditional methods used to predict the ground-wave field strength at low frequency and are not applicable for terrains with serious irregularities because of the analytical approximations. A virtual propagation MATLAB based predictor tool SNELLIX is developed for propagation of EM waves over non-flat terrain through homogeneous and an inhomogeneous atmosphere.
Keywords: Wave propagation, ray tracing, tri linear refractivity, ducting, anomalous propagation, PWE, HFSWR

1. Introduction

Surface wave propagation along multiple mixed propagation paths including irregular terrain profiles has long been a challenging wave-propagation prediction problem. Electromagnetic medium has been well described by James Clerk Maxwell by means of some equations. Such remarkable development and the consequent inventions of radio communications have opened the doors of electromagnetic spectrum for many diverse applications. The early analytical formulations mostly included ray-mode representations in two-dimension (2D) over smooth spherical Earth through homogeneous atmosphere. While since last few decades, the application area of numerical methodologies has been extended up to such great extent that even now includes the approach to model the vertical and/or horizontal refractivity variation effects and irregular terrain profiles onto the surface wave propagation. The propagation of waves in other frequency ranges like such as sound or radio waves behave similar to the propagation of light. Waves propagate as fronts and spread in different directions when interacting with obstacles. During the last decades, lot of research has been performed to understand the behaviour of electromagnetic wave propagation in different mediums. The electromagnetic waves propagated from the transmitter antenna travels in a free space up to receiver antenna. The movement of theses electromagnetic waves takes place by different ways. Each way of propagation is explained as below.

- Ground waves
- Sky Waves
- Space Waves

The radio waves covered under VLF band propagate in a ground, or surface wave where toward one side, the wave is associated with the surface of the earth and to the ionosphere at the other. The ionosphere is the region above the troposphere about 50 to 250 miles above the earth composed of a collection of ions. The ions are fundamentally the atoms having some of their electrons stripped off leaving two or more electrically charged objects behind. The propagation of radio waves in the presence of ions is radically unique than in air which forces it to be used in most modes of propagation. Ground waves support very long range propagation as they follow the duct which is curved along the earth. This duct is actually formed within the earth and the ionosphere limits of ground waves.

Radio waves in the LF and MF at higher frequencies usually suffer significant losses or may get attenuated. Hence such waves are propagated by new mode: the sky wave. Sky waves are in actual the reflections from the ionosphere. While the wave is in the ionosphere, it is strongly bent, or refracted, ultimately back to the ground which appears as reflection from a long distance. Long ranges up to hundreds of miles are possible in this mode only at night, since that time the concentration of ions is not too great and is only much enough to reflect the wave as the ionosphere also tends to attenuate the signal.

The sky waves exclusively deal with the HF band. In contrast to MF, the higher frequencies have less attenuation and less refraction in the ionosphere. At the high end, the waves completely penetrate the ionosphere and become space waves while at the low end, they are always reflected. The HF band operates with both these effects almost all of the time. The characteristics of the sky wave propagation depend on the conditions in the ionosphere which in turn are dependent on the activity of the sun. The ionosphere has several well-defined regions in altitude [Iqbal A. and Jeoti, V. (2012)].

2. Propagation phenomenons

As electromagnetic waves and radio signals travel, they interact with objects and the media in which they travel and consequently undergo different behaviours such as reflection, refraction or diffraction. Hence, the important propagation phenomena are reflection, refraction and diffraction.

Reflection of light is a very common phenomena found in everyday life. When reflection occurs, the angle of incidence is equal to the angle of reflection for a conducting surface and same is expected to happen for light. When a signal is reflected there is normally some loss of the signal, either due to absorption, or as a result of some of the signal passing into the medium.

Reflection can occur through a variety of surfaces. For long distance communications, the sea and other wet areas provide best reflecting surfaces while desert areas and other types of land are poor reflectors. Comparatively for short range communications, many buildings, particularly with metallic surfaces provide excellent reflectors of radio energy. As a result of this signals travelling to and from cellular phones often travel via a variety of paths. Similar effects are noticed for Wi-Fi and other short range wireless communications. An office environment contains many surfaces that reflect radio signals very effectively.

For some radio waves, refraction is also possible. The basic concept of light wave refraction is well known, as it can be easily demonstrated by placing a part of stick or pole in water and leaving the remaining section in air. It is possible to see the apparent change or bend as the stick enters the water. Refraction can also be demonstrated by Mirages and a very similar effect can be noticed on hot days when a shimmering effect can be seen along a straight road. Radio waves also follow it the much same way. When they move from one refractive index to other, the direction of an electromagnetic wave experiences a change. The relationship between the angle of incidence and the angle of refraction is given by Snell's Law that states:

n1 sin (theta 1) = n2 sin (theta 2)

Radio signals rarely move abruptly from a region with one refractive index, to a region with another rather it is comparatively gradual change. This causes the direction of the signal to bend rather than undergo an immediate change in direction.

Diffraction is the third possible case for radio waves. The basic diffraction phenomenon states that when a wave passes through an aperture, it spreads out from the opening. The degree of the diffraction depends on the size of the aperture relative to the wavelength. In the extreme case where the aperture is very large compared to the wavelength, the wave will see no effect and will not diffract at all while if the opening is very small, the wave will behave as if it were at its origin and spread out uniformly in all directions from the aperture.

It is found that on encountering an obstacle, signals often tend to travel around them. This helps to imply that a signal may be received from a transmitter even though it may be "shaded" by a large object between them. This is particularly noticeable on some long wave broadcast transmissions. It is found that diffraction is more pronounced when the obstacle becomes sharper and more like a "knife edge". For a radio signal a mountain ridge may provide a sufficiently sharp edge. A more rounded hill will not produce such a marked effect. It is also found that low frequency signals diffract more markedly than higher frequency ones. It is for this reason that signals on the long wave band are able to provide coverage even in hilly or mountainous terrain where signals at VHF and higher would not.

2.1 *Propagation Models*

Radio propagation models facilitate studies of radio transmissions under different environments of implementation of the radio system. Radio propagation models can be classified in to two categories:

1. Outdoor Propagation Models
2. Indoor Propagation Models

Continuous studies have been going on to find methods for predicting outdoor wireless signal coverage. These models determine the path loss, the difference between the transmit power and received power, from the transmitter to the receiver and predict the signal power. For many years, the outdoor environment has been supporting mobile communications for private and public users, and has seen a great deal of work in characterising the environment in order to utilise the potential bandwidth to its maximum capability.

2.2 *Atmospheric Refractivity*

Due to gradient of refractive index in troposphere, the radio waves do not follow the straight path as in free space; hence, ducts or layers are formed in troposphere. Normally, gradient in refractivity is a fraction of unity. So, convenient way of expressing the refractive index is a term called ‘refractivity’ N, written in terms of refractive index as

$$N = (n - 1)\times 10^{6}$$

Refractivity N depends on other factors and can be expressed as:

$$N = 77.6\frac{P}{T} + 3.73X10^{5}\frac{e}{T2}$$

P= Total atmospheric pressure (in mbar)

T=Atmospheric temperature (in K)

e= partial water vapour pressure (in mbar) and N is dimensionless.

There are three well-known Tropospheric ducts- Surface duct (Ground-based duct), Surface-based duct and elevated duct. In surface and surface-based duct lower boundary of duct is earth's surface, but in elevated duct both lower and upper boundary are above the earth's surface. When radio waves are channelled through these ducts, it behaves differently from normal environment. This non-standard propagation is also referred to as 'anomalous propagation'. Due to ducting phenomenon and earth surface profile, radio wave is affected by reflection, refraction and diffraction mechanisms. Since the occurrence of these mechanisms is dependent on rough surface profiles, it is very difficult to accurately predict the propagation in complex environment [Iqbal A. and Jeoti V. (2011)].

3. Parabolic Equation model

The one-way parabolic equation (PE) method has been one of the widely used propagation tools to model the ground wave propagation over the 2-D Earth's surface because of its flexibility in modeling both horizontally and vertically varying atmospheric refraction effects and irregular terrain paths. The standard parabolic wave equation (PWE) is derived from Helmholtz's equation by eliminating the rapidly varying phase term to obtain a reduced function that has a slow variation in range for propagating angles close to the paraxial direction. Helmholtz's equation is approximated in terms of two differential equations, both of which are in PWE form, belonging to forward and backward propagating waves. In the standard PE method, only the PWE corresponding to the forward part is solved, which makes the method a one-way forward-scatter model [Apaydin, G. and Kuzuoglu. M. (2011)]. The propagation area covers 2D area (0-2X_{max}) in height and (0-Z_{max}) in range. In the figure, source is infused as a surface coupled mode and the maximum height is represented as X_{max}. Homogeneous atmosphere includes earth's curvature (+117 M unit/km) and lies between 0- X_{max}. Artificial lossy layer is assumed between X_{max}-2X_{max}. The figure is also showing paraxial boundary and maximum terrain slope. The upper boundary artificial reflections have been eliminated using a window function.

The scalar wave function can be obtained as the solution of the following 2-D Helmholtz equation:

$$\frac{\partial 2\varphi}{\partial x2} + \frac{\partial 2\varphi}{\partial z2} + k^2n^2\varphi = 0 \qquad [1]$$

Where, $k = 2\pi/\lambda$ is the free-space wavenumber (λ is the wavelength), $n(x, z)$ is the refractive index, and ϕ denotes the electric or magnetic field in horizontal or vertical polarization, respectively. Here, x and z represent range and altitude coordinates, respectively.

By introducing the reduced function as u(x, z) = exp(−ikx)ϕ(x, z), the wave equation in terms of u is given as follows:

$$\left[\frac{\partial 2}{\partial x2} + 2ik\frac{\partial}{\partial x} + \frac{\partial 2}{\partial z2} + k^2(n^2-1)\right] u(x,z) = 0 \qquad [2]$$

The differential operator can be factored in terms of two pseudo-differential operators and put into forward and backward propagating waves, as follows:

$$\frac{\partial u}{\partial x} = \{\ ik(1-Q)u \text{ forward,/ } ik(1+Q)u \text{ backward} \qquad [3]$$

Where $Q=\sqrt{\ }1+q$ and $q=\frac{1}{k2}\frac{\partial 2}{\partial z2} + (n^2-1)$

The formal solution of the forward propagation can be expressed as:

$$u(x+\Delta x, z) = \exp[\ -ik\ \Delta x(1-Q)]\ u(x,z) \qquad [5]$$

which is amenable to numerical solution by marching-type algorithms along range while the backward propagating waves are omitted in the standard PE. The operator Q is approximated by using the first-order Taylor expansion (i.e., $\sqrt{1+q} \approx 1 + q/2$), yielding the standard PE as follows:

$$\left[\frac{\partial 2}{\partial z2} + 2ik\frac{\partial}{\partial x} + k^2(n^2-1)\right] u(x,z) = 0 \qquad [6]$$

The standard one-way PE method, in spite of its wide-spread usage, suffers from two major drawbacks:

(i) The first drawback of PE method is that it deals only the forward-propagating waves and neglects the backscattered waves. Moreover, the forward waves provide also fail to deal with the obstacles as obstacles redirect the incoming wave in the form of reflections and diffractions. However, the accurate estimation of the Multipath effects, occurring during propagation over terrain, requires the correct treatment of backward waves as well. Moreover, the PE method takes the diffraction effects into account within the paraxial approximation, degrading the accuracy of the approach in deep-shadow regions where the diffracted fields dominate.

(ii) The second drawback is that the standard PE restricts the accuracy to propagation angles up to 10◦–15◦ from the paraxial direction hence is most directly applicable within a narrow range of angles about the propagation direction. A typical long-range propagation encounters propagation angles that are usually less than a few degrees, whereas the short range propagation problems, as well as the problems involving multiple reflections and diffractions because of hills and valleys with steep slopes, can only be solved by a PE model that is effective for larger propagation angles, [Ozgun. O, Apaydin, G. Kuzuoglu. M. and Sevgi, L. (2011),].

4. Ray tracing approaches

The ray-tracing method is a high-frequency approximation technique, which requires the dimensions of the objects in terms of wavelengths for accurate results. Ray-tracing based radio wave propagation prediction models play a crucial role in the design of modern wireless networks. Initially, ground wave propagation studies began with considering smooth spherical earth in two-dimensional (2-D) space, and then progressed toward being more realistic through physics-based numerical algorithms, operating in the frequency and short-pulse time domain. A series of simulations for distinguished terrain and atmospheric refractivity's, including different source-receiver arrangements and operating frequencies, established the range of problem parameters for each algorithm. Maxwell equations represent wave propagation in both spatial and time domains in open regions. For realistic propagation prediction, a mathematical model and its discrete implementation must include all relevant scattering components that account for path loss between any two points in a 3-D digitally- parameterized environment. Moreover, the terrain profile, vegetation, Earth's curvature, atmospheric refractivity, and the presence of other obstacles must also be considered [Sevgi, L. (2007)].

The Ray-Tracing method consists of a direct research of geometric paths followed by the waves. The term ray tracing includes two different aspects: Firstly, the determination of a ray trajectory from the transmitter to the receiver; secondly, once this trajectory is available, the determination of the actual field strength of the ray at the receiver by the ray along its trajectory, taking into account all occurring propagation phenomena. The valid ray trajectories can be retrieved from the transmitter to the receiver in a given geometry via ray tracing by direct and indirect methods. Direct methods, like image theory or the rubber band method, directly lead to the exact ray paths. For indirect methods, also called ray launching, a number of rays is launched from the transmitter in arbitrary directions and traced until they eventually hit the receiver or until they surpass a certain maximum attenuation [Didascalou, D., Schäfer, T. M., Weinmann, F. and Wiesbeck, W. (2000)].

5. Motivation

The accurate modelling of the ground wave propagation over the Earth's surface is usually a challenging task because of several complex processes occurring during the propagation. An important surface wave propagation phenomenon under attention is the mixed path propagation problem. Numerous approaches have been developed valid for the smooth spherical Earth but unfortunately unable to take terrain irregularities into account. There are only a few attempts in modelling mixed-path transitions with terrain irregularities. In particular, the terrain irregularities reflect and diffract energy in a complicated way and have a significant impact on the radio wave path loss. Such terrain effects become even more pronounced when coupled with atmospheric refraction because an inhomogeneous atmosphere may redirect energy and cause multiple interactions with the ground.

In order to predict the HFSWR performance, it is utmost essential to understand the propagation characteristics over the Earth's surface along realistic propagation path. Estimation of typical path losses between HFSWR and a target at various operating frequencies requires a "good" propagation model. Ground waves consist of three components: direct waves, ground-reflected waves, and surface waves. As long as the transmitter and receiver are close to surface and/or the range is sufficiently long, the direct and ground reflected waves cancel each other and only SW propagates [Apaydin, G. and Sevgi, L. (2010)]. The environment considered for the present study is a spherical Earth with lossy, irregular/rough surface with a variable refractivity. There exist numerous approximate analytical and pure numerical techniques to deal with the problem in two-dimensions (2D) still the exact solution of this complex problem is yet to be solved [Ozgun. O, Apaydin, G. Kuzuoglu. M. and Sevgi, L. (2014)].

6. Proposed approach

A model has been proposed to visualize the surface wave propagation in different scenarios, variable terrains and varying refractivity profiles like tri linear and bilinear refractivity profiles that too in both homogeneous and in homogeneous atmosphere.

An approach has been proposed to visualize the surface wave propagation in three scenarios. One without obstacles, second with obstacles and the third one is including tunnel.

7. Simulation results

The proposed approach has been implemented in MATLAB and virtual propagation predictor tool SNELLIX is developed whose results show ray propagation in different scenarios. First one is SNELL's law in different media one, two or three media. Then different results for homogeneous and non-homogeneous atmosphere considering concept of ducting, anti-ducting, elevated-ducting, tri linear and bilinear refractivity are presented.

Tunneling effect is that in which ray begins to merge towards central point of horizon. This effect is the basis of X-ray telescopes EM wave propagation through tunnels. EM wave propagation in tunnels is also an important aspect to consider along with outdoor scenario. For underground applications in complex conditions, standard laws are not valid .So one aim of this predictor tool is to model EM wave propagation through curved and non-rectangular cross section.

Four kinds of tunnel geometries are normally encountered as written below:

- triangular tunnel
- straight rectangular tunnel
- curved rectangular tunnel

curved circular tunnel

8. Conclusion

Virtual Surface wave propagation predictor tool SNELLIX is designed and discussed in this paper. This tool can be used in various fields like to explain and develop various models based on "EM Wave Theory", "Antenna and Propagation Concepts", "Wireless Communication Aspects" and it can also be used as research tool at higher level to explain and develop ducting/anti-ducting scenarios with varying refractivity profiles. It is very useful in understanding concepts of wireless transmission and in future more advanced 3D models can be built even with negative refractivity profiles to do outdoor propagation more efficiently.

References

Zhou, L., Xi, X., Liu, J. and Yu, N. , "*LF Ground-Wave Propagation Over Irregular Terrain*", IEEE transactions on antennas and propagation, vol. 59, no. 4, pp. 1254-1260, 2011.

Iqbal A. and Jeoti V. "*Numerical Evaluation of Radio wave Propagation in Evaporation Ducts using FEM*", 978-1-4577-1884-7/11©2011 IEEE ,2011 .

Iqbal A. and Jeoti, V., "*Numerical Modeling of Radio Wave Propagation in Horizontally Inhomogeneous Environment Using Split-Step Wavelet Method*", Proceedings of 4th International Conference on Intelligent and Advanced Systems, Malaysia, pp. 200-205, 2012.

Apaydin, G. and Kuzuoglu. M. (2011), *"A Novel Two-Way Finite-Element Parabolic Equation Groundwave Propagation Tool: Tests with Canonical Structures and Calibration*", IEEE transactions on geoscience and remote sensing, vol. 49, no. 8, pp. 2887-2899. Ozgun. O, Apaydin, G. Kuzuoglu. M. and Sevgi, L. (2011), *"PETOOL: MATLAB-based one-way and two-way split-step parabolic equation tool for radiowave propagation over variable terrain", journal of Computer Physics Communications, vol 182, pp. 2638-2654* Sevgi, L., "*Groundwave Modeling and Simulation Strategies and Path Loss Prediction Virtual Tools*", IEEE transactions on antennas and propagation, vol. 55, no. 6, pp. 1591-1598 , 2007.

Didascalou, D., Schäfer, T. M., Weinmann, F. and Wiesbeck, W., "*Ray-Density Normalization for Ray-Optical Wave Propagation Modeling in Arbitrarily Shaped Tunnels*", IEEE transactions on antennas and propagation, vol. 48, no. 9, pp. 1316-1325, 2000.

Apaydin, G. and Sevgi, L., "*Propagation modeling and path loss prediction tools for high frequency surface wave radars*", Turk J Elec Eng & Comp Sci, Vol 18, No.3, 2010.

Ozgun. O, Apaydin, G. Kuzuoglu. M. and Sevgi, L., "*Propagation Modeling Over Irregular Terrain by the Improved Two-Way Parabolic Equation Method*", IEEE transactions on antennas and propagation, vol. 62, no. 7, 2014.

Apaydin, G. and Sevgi, L., "*Numerical Investigations of and Path Loss Predictions for Surface Wave Propagation over Sea Paths Including Hilly Island Transitions*", IEEE transactions on antennas and propagation, vol. 58, no. 4, pp. 1302-1314, 2010.

CHEW, W.C. and GIANZERO, S. C., "*Theoretical Investigation of the Electromagnetic Wave Propagation Tool*", IEEE transactions on geoscience and remote sensing, vol. ge-19, no. 1, pp. 1-7, 1981.

Mahmoud, S. F., and Antar, Y. M. , "High frequency ground wave propagation", IEEE transaction on antennas and propagation, vol. 62, no. 11, pp. 5841-5846. Marcus, S. W. (1992), "A Hybrid (Finite Difference-Surface Green's Function) Method for Computing Transmission Losses in an Inhomogeneous Atmosphere Over Irregular Terrain", IEEE transactions on antennas and propagation, vol 40, no 12, pp. 1451-1458, 2014.

Tam, W. K., and Tran, V. N. , "Propagation modelling for indoor wireless communication", Journal of electronics & communication engineering, vol. 7, no. 5, pp. 221-228, 1995.

Yang, C. F., Wu, B. C. and Ko, C. J., "A Ray-Tracing Method for Modeling Indoor Wave Propagation and Penetration", IEEE transactions on antennas and propagation, vol. 46, no. 6, pp. 907-919, 1998.

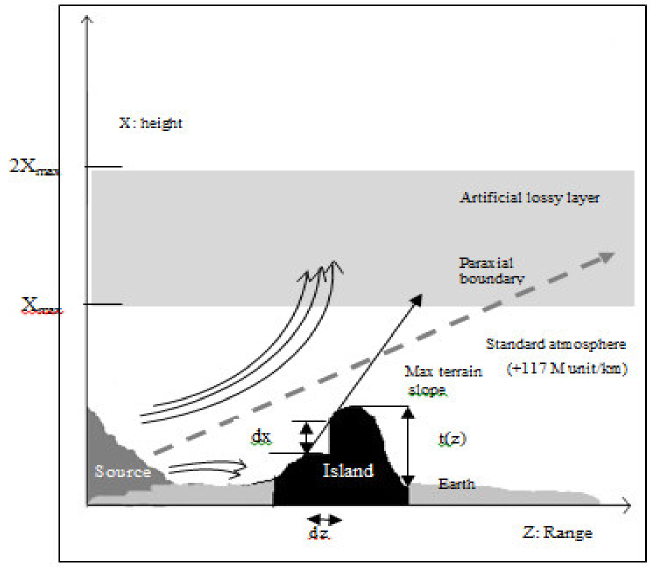

Figure 1. The 2D surface wave propagation

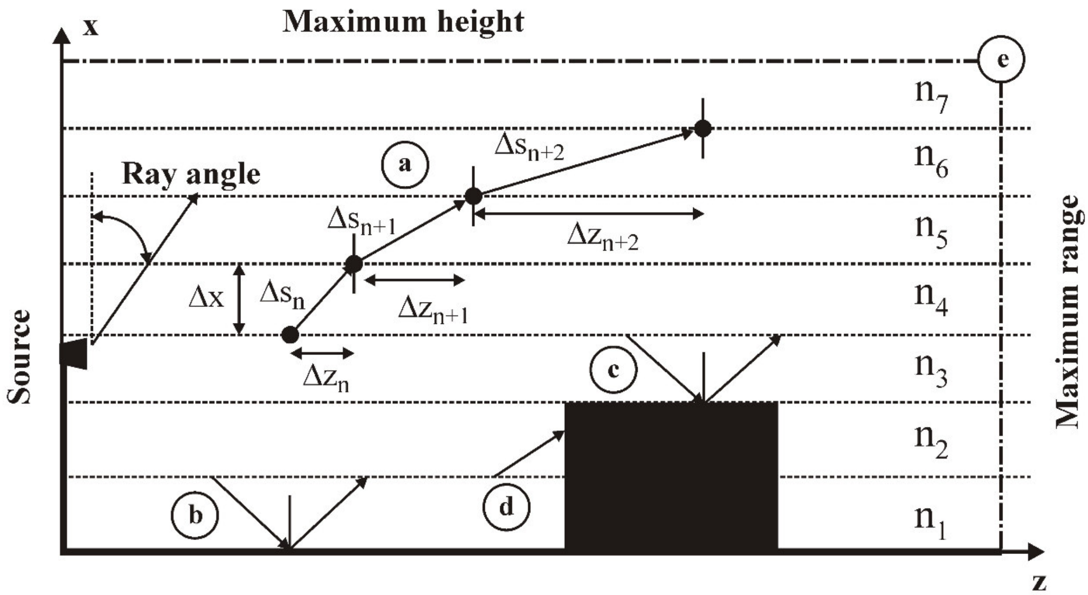

Figure 2. 2-D propagation environment with a PEC obstacle in (x,z) coordinate system. The medium constitute multiple planar layers with refractive indices n1, n2, and so on. The height of each layer is user selected and is represented as Δx. The ray path segments and the range segments represented as ΔS and ΔZ respectively and are determined by Snell's Law. The figure shows the reflections taken place at the obstacles and the maximum height and range.

(a) represents the consecutive applications of Snell's law and the consecutive calculations of ΔS and ΔZ.
(b) reflection taking place at PEC bottom surface
(c) shows the reflection occurred at the top surface of the obstacle
(d) shows the ray ending at left side of the PEC obstacle
(e) shows the maximum height and range of the considered propagation environment

Ray bending occurs when a ray caustic is formed means when the angle of reflection is closer to 90.

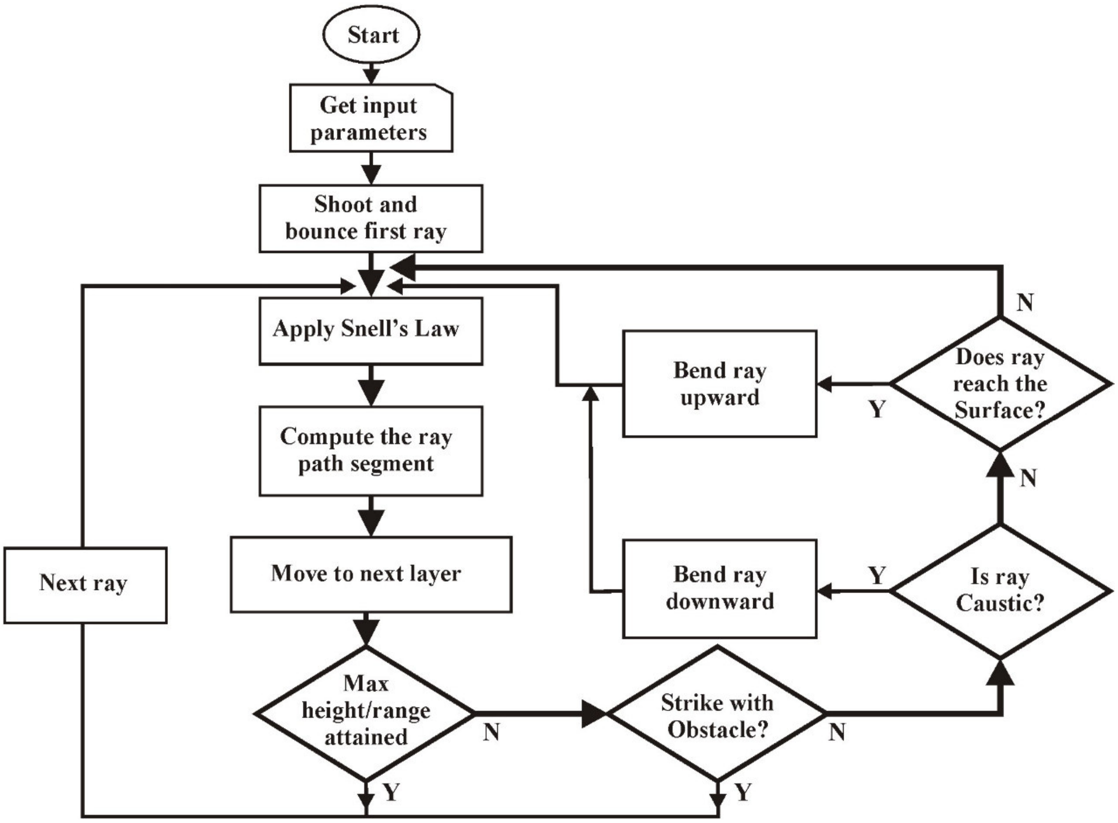

Figure 3. Flowchart of the proposed approach where the user inputs the various parameters namely- Max. Range and Height, Height of layers, Source location, First and last angles measured from Surface Normal, Tri Linear Refractivity parameters, Ray Increment, heights and location of obstacles. The ray shooting is performed. The flowchart shows the ray propagation loop with the help of thick arrows and ray loop with the help of thin arrows. At the point when maximum range or height is reached, the algorithm shoots the next ray.

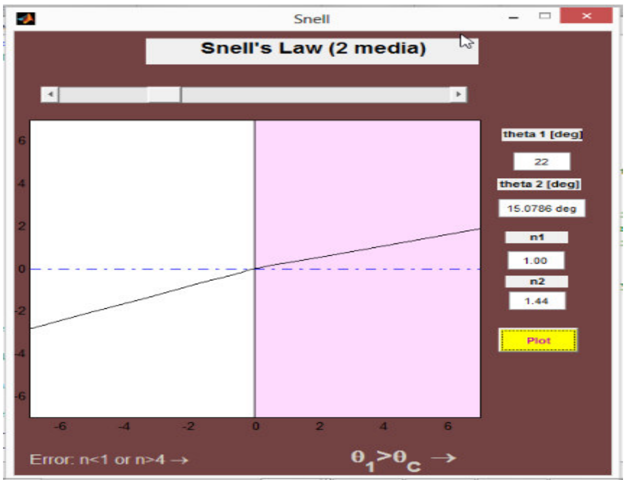

Figure 4. Snell's Law deals with bending of light when travelling from one medium to another. In this result it is travelling from Air (refractive index=1.00) to optical fibre composed of Silica (refractive index=1.44), rarer to denser medium and it refracts towards the normal (when slowing down while crossing the boundary).

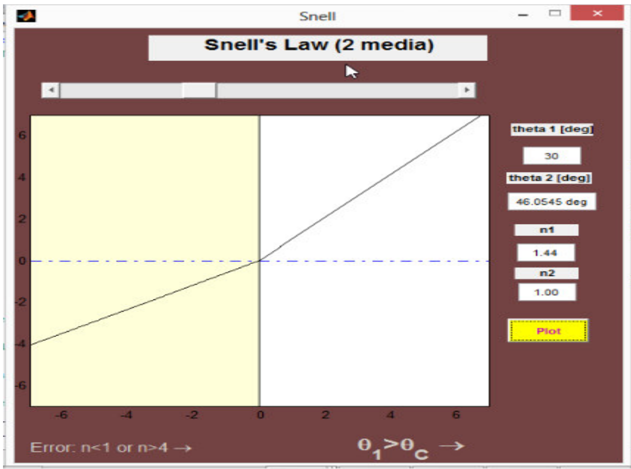

Figure 5. In this result it is travelling from optical fibre composed of Silica (refractive index=1.44) to Air (refractive index=1.00), denser to rarer medium and it refracts away from the normal (when speeding up while crossing the boundary)

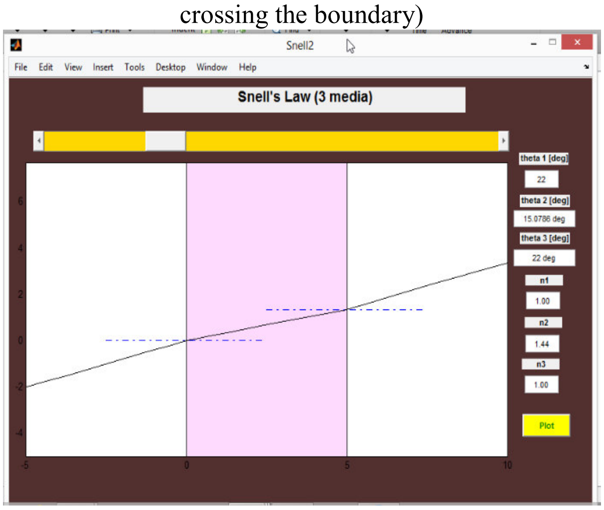

Figure 6. This result shows three media Snell's Law in which light is firstly travelling from air to fibre and then back from fibre to air. It shows combined phenomenon of bending towards and away from the normal.

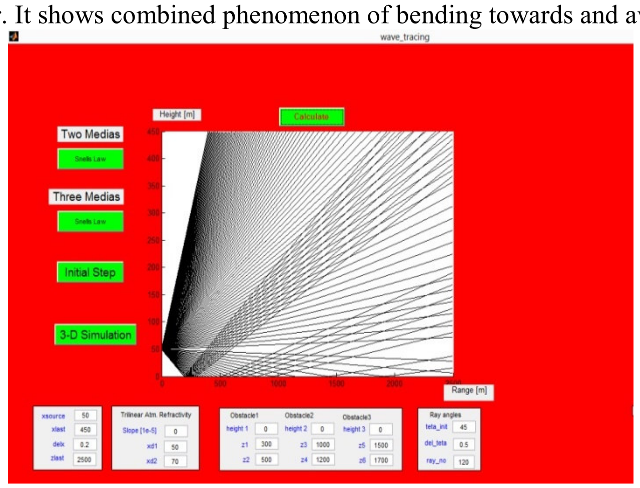

Figure 7. Snellix Model's front end design is shown in this result for homogeneous atmosphere with constant refractive index. Rays are travelling in rectilinear mode means in straight lines(height of source=50 m, last height=450 m, difference in layers=0.2,last range=2500 m ,ray shooting first and last is 45° and 120° respectively with increment in ray angle is 0.5°) all parameters are user defined and can be modified as per requirements, environmental and atmospheric conditions.

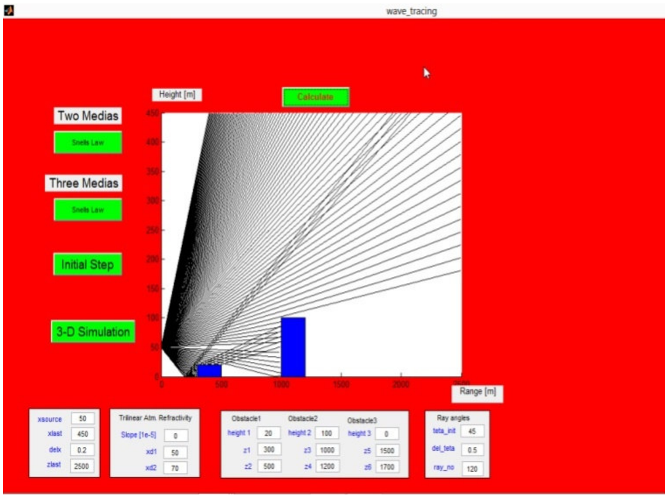

Figure 8. In it reflections from top of buildings and ending of rays at PEC (Perfect Electrical Conductor) are observed clearly (height of source=50 m, last height=450 m, difference in layers=0.2, last range=2500 m, ray shooting first and last is 45° and 120° respectively with increment in ray angle is 0.5°, height of first obstacle is 20 m and that of second obstacle is 100 m with range 300 m and 1000 m respectively)

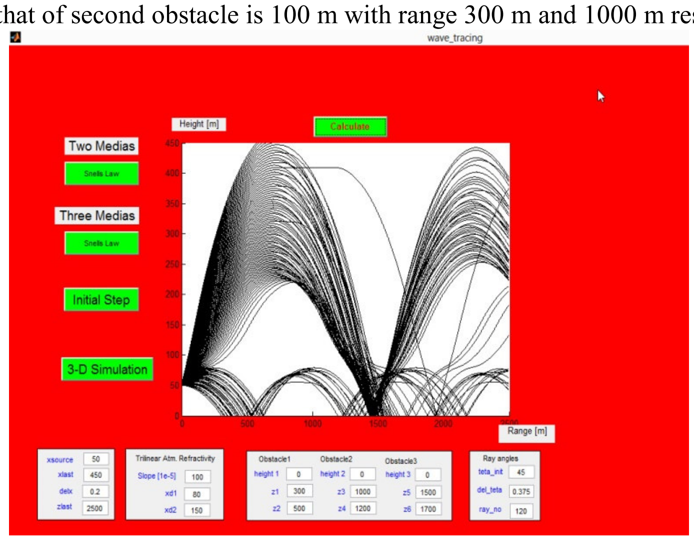

Figure 9. In it tri-linear refractivity profile is considered with no obstacles. Typical phenomena are clearly observed.

a) Reflection
b) Refraction
c) Bending
d) Caustics (height of source= 50 m, last height= 450 m, difference in layers= 0.2 ,last range = 2500 m, ray shooting first and last angles are 45° and 120° respectively with increment in ray angle is 0.375°, tri linear refractivity slope is 100 having ducting and anti-ducting scenario).

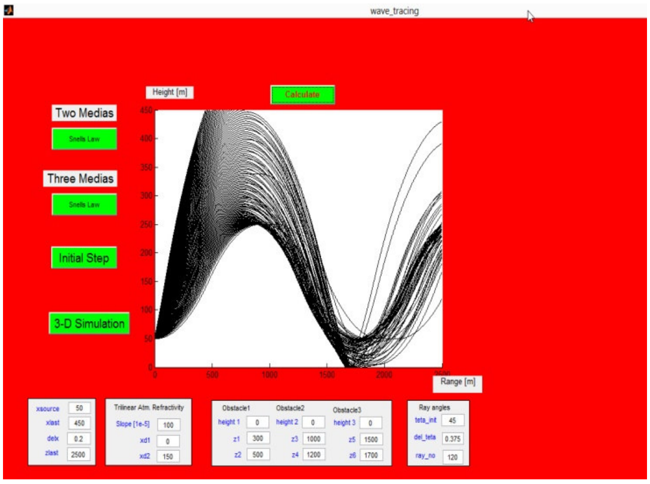

Figure 10. In it bi-linear refractivity is shown with the concept of elevated ducting, in elevated ducting, height is taken as 0 m and elevated duct formation can be changed by changing parameters like tri-linear slope refractivity and source height).

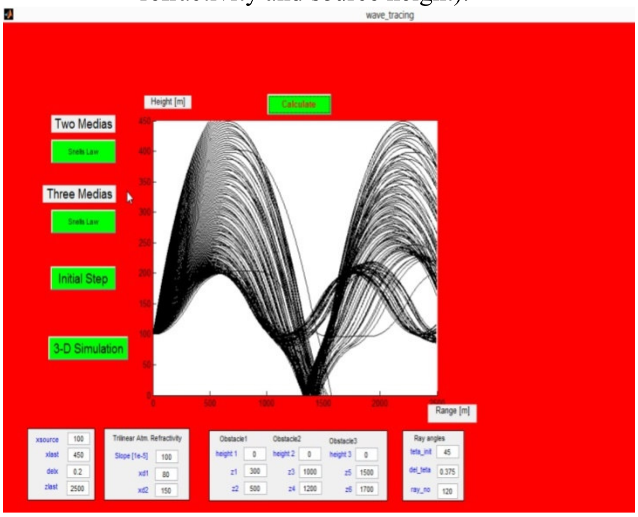

Figure 11. In it tri-linear refractivity is there but location of source has been changed and no consideration of obstacles.

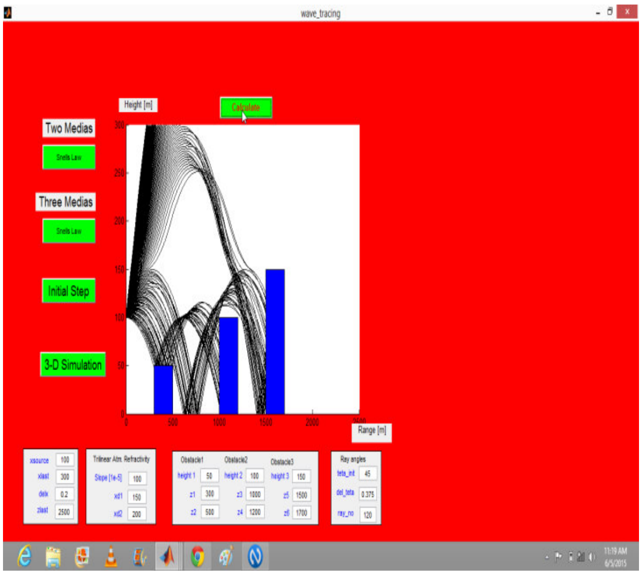

Figure 12. In it strength of signals has been shown, signals ranging between 500 m and 1000 mare weak in strength compared to another ranges, darkness in various regions shows multiple rays and it can be area of maximum field intensity as well as minimum field intensity, like constructive and destructive interference,

illuminated region and shadowed portion is clearly visible.

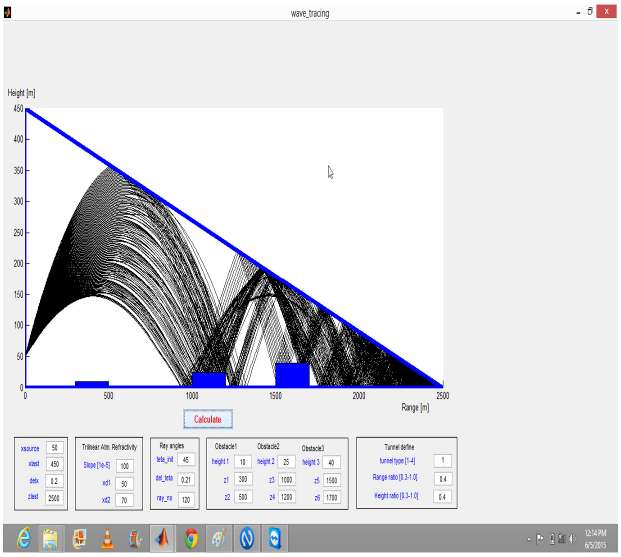

Figure 13.This result shows tunnel geometry having triangular shape

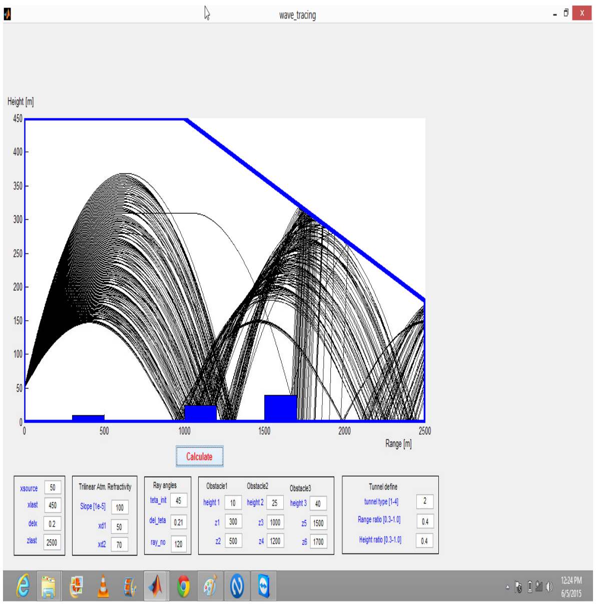

Figure 14. This result shows tunnel geometry having half cut straight rectangular shape.

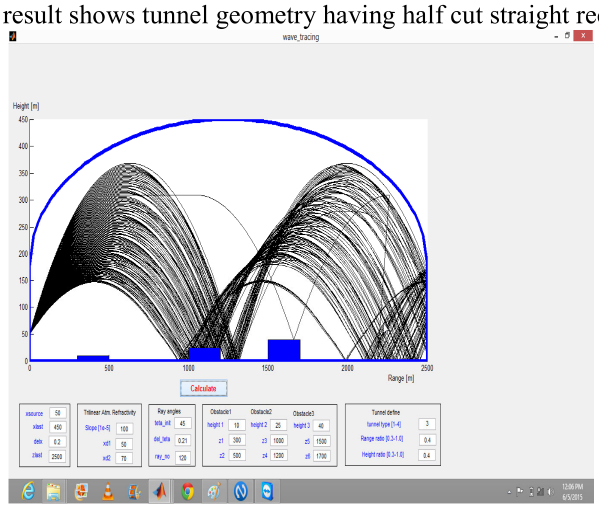

Figure 15. This result shows tunnel geometry having curved semicircular shape.

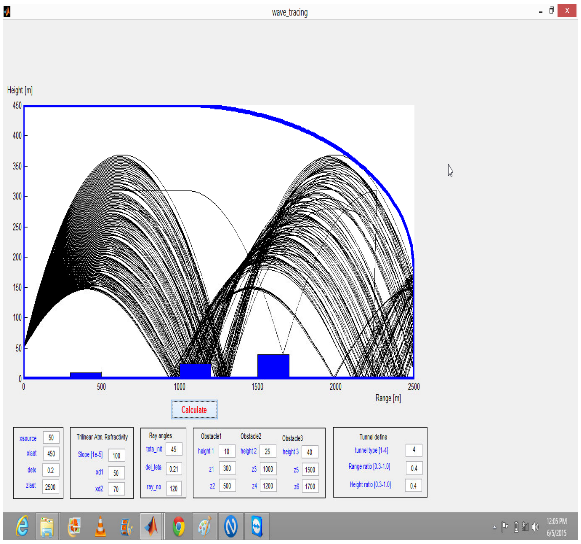

Figure 16 .This result shows tunnel geometry having curved rectangular shape.